

Current-voltage characteristics and vortex dynamics in highly underdoped $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$

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Abstract The temperature dependence of the nonlinear current-voltage (I - V) characteristics in highly underdoped $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ ($x=0.07$ and 0.08) thick films has been studied in both zero and perpendicular magnetic fields H . Power-law behavior of $V(I)$ is found for both $H = 0$ and $H \neq 0$. The critical current I_c was extracted, and its temperature and magnetic field dependences were studied in detail. The Berezinskii-Kosterlitz-Thouless physics dominates the nonlinear I - V near the superconducting transition at $H = 0$, and it continues to contribute up to a characteristic temperature $T_x(H)$. Nonlinear I - V persists up to an even higher temperature $T_h(H)$ due to the depinning of vortices.

Keywords nonlinear current-voltage · Berezinskii-Kosterlitz-Thouless · vortices · cuprates

1 Introduction

In underdoped cuprates, which are layered materials with weak interlayer coupling, studies of paraconductivity have shown a strong 2D character of the superconducting fluctuations [1,2]. However, the existence of a Berezinskii-Kosterlitz-Thouless (BKT) transition in bulk cuprates has been controversial [3,4,5]. For example, the penetration depth measurements in bulk $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ found no signatures of the BKT physics in thick films [6] or crystals [7], while dc transport measurements suggested BKT-like behavior in bulk samples of several cuprates (see, *e.g.*, Refs. [8,9,10,11]). A recent study of the paraconductivity and the I - V characteristics in highly underdoped $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ ($x = 0.07$ and

0.08) thick films (150 \AA CuO_2 layers) in zero magnetic field [5] showed that the effective dimensionality of the samples is 2D, and that the thermally-driven transition to the superconducting state is of the BKT type with a large vortex-core energy $\mu \approx 1.4\mu_{XY}$ ($\mu_{XY} = \pi^2 J_s/2$ is the conventional value that it assumes in the XY model; J_s is the superfluid stiffness). At the BKT transition, J_s jumps from 0 above T_{BKT} to $2T_{BKT}/\pi$ at T_{BKT}^- , leading to a change from linear to super-linear behavior in the I - V characteristics: $V \propto I^{a(T)}$, where $a(T) (= \pi J_s/T + 1)$ jumps from 1 to 3. T_{BKT} was determined to be 4.0 K and 9.7 K for the $x = 0.07$ and $x = 0.08$ samples, respectively [5]. The presence of inhomogeneities leads to some smearing of the transition, giving rise to finite superfluid stiffness even for $T > T_{BKT}$ [5]. Here we present a detailed study of the evolution of the $I - V$ characteristics of the same $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ (LSCO) samples in a perpendicular magnetic field H .

At small fields, H -induced free vortices coexist with BKT-like thermally generated vortex-antivortex pairs [12,13,14]. As H increases, vortex-antivortex pairs break and H -induced free vortices proliferate, leading to novel phases of the vortex matter [15,16]. Indeed, in the same underdoped LSCO films, two quantum critical points have been found to associate with boundaries of different vortex phases [17]. In general, both the BKT physics and the physics of vortex matter have been subjects of intensive studies, but they have been mostly treated as two separate topics [4,15,16]. Some efforts have been put forward to treat the BKT physics in a magnetic field and vortex matter physics on the same footing [18,19], though much remains to be understood. The goal of our study is to bridge the BKT physics and the physics of vortex matter.

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2 Experiment

The samples were ≈ 100 nm thick LSCO films with $x = 0.07$ and $x = 0.08$, grown by molecular beam epitaxy. The samples have been described in detail elsewhere [5,20]. The mean-field transition temperature T_c was determined to be 6.5 K and 11.3 K for the $x = 0.07$ and $x = 0.08$ samples, respectively [5]. Standard four-probe I - V measurements were performed up to 9 T ($H \parallel c$ -axis). A low-pass pi-filter was used to eliminate current noise that leads to Ohmic tails at low excitations [21]. Great care was taken to exclude Joule heating effects, including (1) a comparison of the I - V measurements using dc current and pulsed current (50 μ s pulse width) and (2) a comparison of the R vs. I curve with the R vs. T curve for different H .

From the I - V characteristics, the critical current I_c is determined as the intersection of a power-law fit at 100 nV, just above the noise background. At large H where BKT physics is absent, this I_c indicates the onset of depinning in the vortex matter description, similar to previous studies in conventional superconductors [22] and in cuprates [23]. For the zero-field BKT transition, however, the regime for non-linear voltage response is bounded by lower and upper critical currents. Below the lower critical current, the system exhibits Ohmic behavior due to finite-size effects [24]. On the other hand, above the upper critical current, Ohmic behavior occurs from Cooper pair depairing and a return to the normal state [25]. Although our definition of I_c is, strictly speaking, neither of these, I_c as defined here will still be a measure of excitation needed to observe nonlinear I - V in the sample. Most importantly, since similar definitions of I_c have already been used in other studies of I - V characteristics in both $H = 0$ [26] and $H \neq 0$ cases [22,23], using this criterion for I_c becomes a bridge that helps address the crossover regime at small fields where both BKT physics and vortex matter dynamics are relevant.

3 Results and Discussion

From the I - V measurements at $H = 0$ for the $x = 0.07$ and $x = 0.08$ samples, $I_c(T)$ were extracted, as shown in Fig. 1. Near T_{BKT} , I_c decreases exponentially as T increases and disappears when the superfluid stiffness J_s becomes zero and the exponent a becomes 1 (e.g. near 6 K for the $x = 0.07$ sample [5]). The data are best fitted with $I_c = I_0 e^{-T/T_0}$, where T_0 is 0.27 ± 0.01 K and 0.35 ± 0.01 K for the $x = 0.07$ and $x = 0.08$ samples, respectively. The strong, exponential dependence of $I_c(T)$ at $H = 0$ is an interesting result and has not been reported to the best of our knowledge.

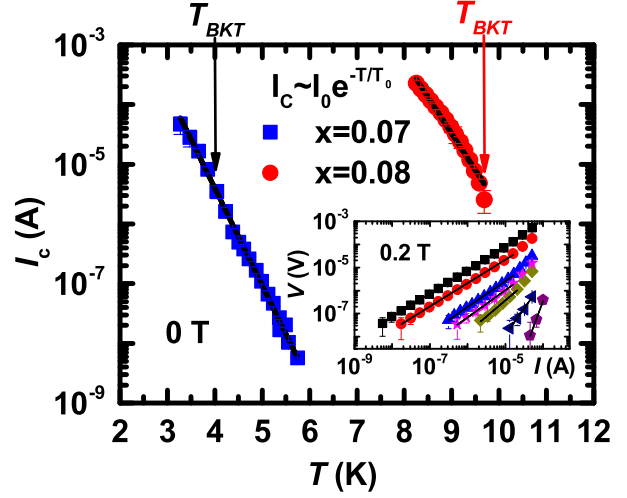


Fig. 1 I_c vs. T is plotted on a semi-log scale for the $x = 0.07$ and $x = 0.08$ samples at $H = 0$. T_{BKT} is marked with arrows. Dashed lines show exponential fits $I_c = I_0 e^{-T/T_0}$ for both samples, where T_0 is 0.27 ± 0.01 K and 0.40 ± 0.01 K for $x = 0.07$ and $x = 0.08$, respectively. Inset: $V(I)$ for the $x=0.07$ sample in $H = 0.2$ T, plotted on a log-log scale for $T = 4.5$ K, 4.0 K, 3.4 K, 3.2 K, 2.5 K and 2.0 K (from top to bottom). Solid lines are fits.

The nonlinear $V(I)$ characteristics in $H \neq 0$ have been studied in detail for the $x = 0.07$ sample. Figure 1 inset shows the typical traces of $V(I)$ at 0.2 T for various T from 2.0 K to 4.5 K. Power-law fits $V \propto I^{a(T)}$ were obtained in the lowest current regime at each T , and a change from nonlinear $V(I)$ at low T to linear $V(I)$ at high T was observed. This power-law behavior of $V(I)$ at $H \neq 0$ bears a close resemblance to that at $H = 0$, though the underlying physics is more complicated. First, it could have contributions from the BKT physics [12,13,14,18]. In addition, the presence of a finite H facilitates the formation of the vortices along the field direction and suppresses the vortices in the opposite direction. As H is increased, the density of vortices increases and the BKT physics becomes less relevant [16]. Vortices are pinned as soon as they are formed and a critical force (current) is needed to depin them. Therefore, the vortex matter dynamics also contributes to the power-law behavior of $V(I)$. The role of excitation current changes from breaking apart vortex-antivortex pairs in the BKT scenario to inducing flux creeps (for small I) and depinning the vortices (for large I) in the vortex matter scenario. We note that we did not observe any exponential $V(I)$, such as that suggested by Kim-Anderson flux creep model [27].

As H increases, I_c at a given T is suppressed, but $I_c(T)$ remains near-exponential (Fig. 2). The fact that $I_c(T)$ does not change abruptly seems to suggest a crossover regime in the $H - T$ phase diagram where the

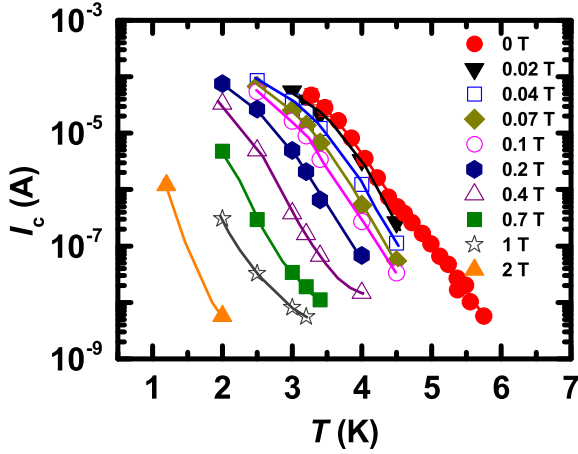


Fig. 2 Critical current I_c vs. T for several H for the $x = 0.07$ sample. The solid lines guide the eye.

BKT physics is still important, consistent with magnetometry measurements in $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ single crystals [14]. Above ~ 0.4 T, the curvature of the $I_c(T)$ on the semi-log scale changes its sign, and $I_c(T)$ no longer resembles its zero-field counterpart, suggesting that the effect of BKT physics becomes negligible. Different regimes can be distinguished more clearly from the $I_c(H)$ dependence, as discussed below. Here we note that the observed near-exponential decrease of $I_c(T)$ is consistent with early studies on vortex matter in other cuprates at much higher doping [23,28]. It was attributed to the melting of the vortex lattice [23] or a vortex glass phase with $I_c \propto I_0 \exp[-(T/T_0)^n]$, where n depends on the ratio of the electronic mean free path to the superconducting coherence length [28]. Here we suggest that the BKT physics may also need to be taken into account.

Figure 3 shows that $I_c(H)$ at low T exhibits a kink-like feature that separates the low- H regime, where I_c varies relatively slowly with H , from the high- H regime, where I_c drops sharply with H . This kink-like feature, as well as the nonlinearity of $V(I)$, are suppressed with increasing T , and disappear above 4.5 K. Two different regimes of $I_c(H)$ were also observed in some previous studies of conventional superconductors [22,30,31]. In those studies, I_c is independent of H in the low- H regime, and it evolves into a power-law behavior, $I_c \propto H^m$ with $m \sim -1$, in the high- H regime. These observations were interpreted as signatures of individual vortex pinning in the low- H regime and collective pinning in the high- H regime. In Fig. 3, a $I_c \propto H^{-1}$ line, expected from the Larkin-Ovchinnikov (LO) theory of collective pinning [29], is drawn for comparison. In our samples, I_c does tend to saturate at the lowest H , consistent with individual vortex pinning, but it decreases

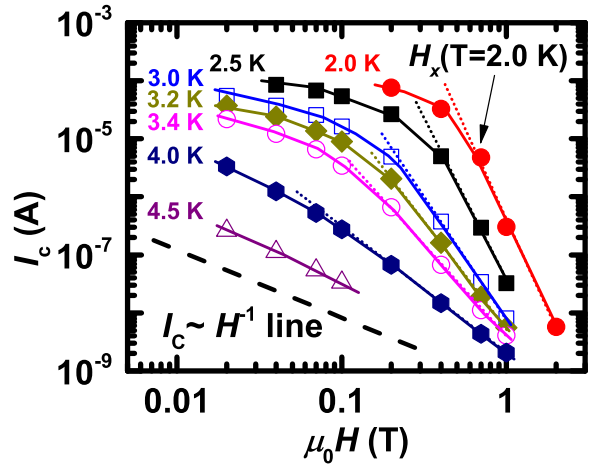


Fig. 3 Critical current I_c vs. H at several T for the $x = 0.07$ sample. Solid lines guide the eye. The dashed line represents $I_c \propto H^{-1}$, which is expected from the Larkin-Ovchinnikov theory of collective pinning [29]. Dotted lines are linear fits, on a log-log scale, to the data in the high- H regime. The crossover fields $H_x(T)$ are identified as fields below which the $I_c(H)$ data start to deviate from the high-field fits.

much faster in the high- H regime compared to the prediction of the LO theory (*e.g.* $m \sim -6$ at 2.0 K). The rather sharp drop of I_c at high H indicates that the weak collective pinning picture of the LO theory is not sufficient in our highly underdoped LSCO films.

The onset of the high- H regime is identified as shown in Fig. 3. It is striking that the corresponding crossover fields $H_x(T)$, *i.e.* crossover temperatures $T_x(H)$, follow closely $T_{R=0}(H)$ (Fig. 4), the temperatures at which the resistance drops to zero. The $T_{R=0}(H)$ line was interpreted as the transition between a pinned vortex solid (Bragg glass) and an unpinned one [17]. Nevertheless, $V(I)$ remains nonlinear up to $T_h(H)$ (the discrete drop and the apparent step in $T_h(H)$ in Fig. 4 are due to the limited resolution of our data; we expect $T_h(H)$ to change smoothly as suggested by the dashed guide line). $T_l(H)$ in Fig. 4 is the temperature below which there are no data available. Therefore, we identify three regimes in the phase diagram. Up to $T_x(H)$, $V(I)$ is nonlinear due to both the BKT physics and the depinning of vortices. Between $T_x(H)$ and $T_h(H)$, the nonlinear $V(I)$ is due to the depinning of vortices and the BKT physics is not relevant. Above $T_h(H)$, $V(I)$ is linear and vortices are no longer pinned.

Finally, since the presence of inhomogeneities leads to finite J_s up to ~ 6 K ($> T_{BKT} = 4$ K) in $H = 0$ [5], we note that it is reasonable to expect that their effect may be important up to $T_h(H)$, giving rise to nonlinear $V(I)$ over extended T and H ranges. Interestingly, signatures of the BKT physics in a magnetic field have also been observed in strongly disordered conven-

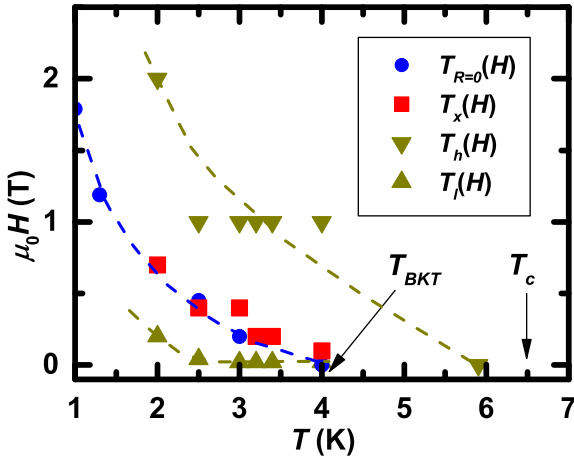


Fig. 4 The $H-T$ phase diagram determined from the $I-V$ characteristics for the $x = 0.07$ sample. $T_x(H)$ denotes the crossover between the low- H and high- H regimes in Fig. 3. $T_{R=0}(H)$ is the temperature at which the resistance goes to zero [17]. $T_h(H)$ is the temperature scale above which $V(I)$ becomes linear. $T_l(H)$ marks the temperature below which there are no data available. $T_{BKT} = 4.0$ K and $T_c = 6.5$ K [5] are marked by arrows. Dashed lines guide the eye.

tional superconductor films [32]. It was suggested that the pinning and creep of vortices in a strongly disordered vortex lattice dominates over melting phenomena associated with a clean system. Therefore, it would be interesting to extend our studies to LSCO at higher doping where the inhomogeneity is smaller.

4 Summary

Our study of the nonlinear $V(I)$ in highly underdoped thick films of $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ at different T and perpendicular H reveals a change in the vortex dynamics at a characteristic temperature $T_x(H)$. In $H = 0$, the superconducting transition is of the BKT type [5]. As H increases, the nonlinear $V(I)$ has its origin in both the BKT physics and the depinning of vortices until $T_x(H)$ is reached. Above $T_x(H)$, the BKT physics becomes irrelevant but the depinning of vortices continues to contribute to nonlinear $V(I)$ up to an even higher temperature $T_h(H)$.

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